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MODIFICATION OF LARGE-DISPLACEMENT, ELASTIC/PLASTIC COMPUTER CODE

University of New Mexico
Albuquerque, NM 87117

August 1977

Final Report

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

AFWL-TR-77-58

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The capability of AFWL/DES to analyze certain classes of cratering problems (e.g., cratering in a thinly layered media) has been limited by difficulties that one of the currently used computer codes has in processing problems in which both strength and material mixing are significant. An attempt to rectify this limitation was made by implementing the engineering equation-of-state presently being used for cratering calculations into an existing large-displacement, elastic/plastic computer code (CSQII). The modified code was then evaluated.

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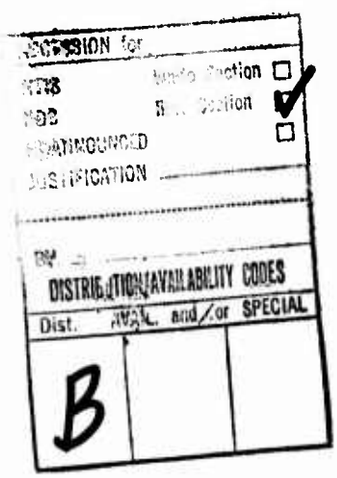

ILLUSTRATIONS

SECTION 1
INTRODUCTION

BACKGROUND

The present AFWL/DES ground-shock and cratering computer code (AFTON) has internal difficulties which limit its ability to perform calculations of large, turbulent deformations in regions in which material mixing and material strengths are significant. This limitation has led to severe problems when attempting to model late-time, earth material response to high-explosive detonations. This problem can be remedied by modifying the CERF version of the Large-Displacement, Elastic/Plastic Computer Code (LDEPCC). This code, CSQII, originally developed to calculate large deformations resulting from underground nuclear detonations, has been applied to cratering by hypervelocity impacts on steel and aluminum plates.

OBJECTIVE

The purpose of this effort was to modify the CERF version of LDEPCC so as to make it compatible with the AFWL/DES ground-shock and cratering calculational needs, and thereby enable the Air Force to increase its knowledge and understanding of nuclear effects on hardened, protective structures.

SCOPE

After the performance of a test case to check the validity of the results of the code against an available exact solution, the material models derived from Cylindrical In-Situ Test (CIST) 15 were to be used to compare the calculated and observed large-deformation, earth material response of the Pre-Dice Throw 100-Ton TNT Event. This evaluation could not be performed because of difficulties in the treatment of mixed material cells; however, a special test was performed as a partial evaluation.

SECTION 2
CSQ II COMPUTER CODE

CSQ II is a Fortran program, written by Dr. Samuel L. Thompson of Sandia Laboratories, for the computation of two-dimensional material motion in either a rectangular or a cylindrical coordinate system (ref. 1). A Eulerian finite-difference method is employed with a high degree of automation built into the program string. Simultaneous energy flow resulting from radiation and thermal conduction can be treated as well as a variety of solid dynamic properties. Many aspects of CSQ II are similar to those of the one-dimensional code CHART D; in particular the CHART D equation-of-state is used in CSQ II.

Essentially CSQ II is a hybrid of Lagrangian and Eulerian methods. During each cycle of computation the mesh is treated as materially fixed, and a complete Lagrangian calculation is performed as the mesh moves with the material. After this phase the code enters a rezoning, or Eulerian section, in which the entire mesh is redefined and moved back to the position it had before the Lagrangian phase.

A unique feature of CSQ II is the retention of cell void volumes. This is necessary for the computation of solid material responses in the Eulerian method, since edges of solids and interior spalling can be properly handled only in this manner.

The standard version of CSQ II, which can treat up to 400 meshes in either spatial coordinate system (160,000 cells), requires $130{,}000_8$ to $270{,}000_8$ words of central memory (CM) on the CDC 7600, depending on the number of different materials in the problem and the number of special routines required (e.g., high explosives, energy flow, etc.).

---

1. Thompson, S. L., *CSQ -- A Two-Dimensional Hydrodynamic Program with Energy Flow and Material Strength*, SAND 74-0122, Sandia Laboratories, Albuquerque, New Mexico, August 1975.

The program retains the complete identity of each material (up to ten) present in the calculation. For each material over two, three additional cell storage variables are required. From 9 to 40 variables per cell are retained, depending on the problem; a special preprocessor program is used to tailor the storage to the problem.

The main cell storage arrays are packed to avoid wasted space. The packed arrays are kept in extended core storage (ECS), with only a small portion of the entire array held in CM at any time. In practice, the largest problem (in terms of the number of cells) is limited by the amount of ECS available.

Four optional subroutine sets may be used with CSQ II. The following additional CM capacity is required when these optional sets are used:

Energy Flow	3500_8
Elastic/Plastic	3400_8
Energy Sources/ High Explosives	2300_8
Internal Fixed Mesh	500_8

The CSQ II package contains seven programs and their general functions are as follows:

(1) PRECSQ — Preprocessor. Tailors storage arrays of remaining programs. (Must be used before any of the remaining programs.)

(2) CSQGEN — Generator. Generates new problems and rezones results of previous calculations.

(3) CSQ — Main Program. Runs problems.

(4) CSQLINE — One-Dimensional Plot Program

(5) CSQPLT — Two-Dimensional Plot Program

(6) CSQSURF — Three-Dimensional (Surface) Plot Program

(7) CSQTAP — Output Data Tape Editor

SECTION 3
IMPLEMENTATION

The only modification required to implement the basic CSQ II on the AFWL CDC 7600 System was the addition of a subroutine. This subroutine (HOROLOG), which supplies date, time, and time remaining in the computer run, is a library subroutine in the Sandia Laboratories CDC 7600 System but does not exist on the AFWL System. However, HOROLOG was included simply by combining AFWL System Library Subroutines XTIME, DATE, and TIME.

Validation of CSQ II consisted of examining the velocities and displacements produced by applying a constant pressure over a spherical surface buried in a multilayered geology. These responses were compared to an exact analytic elastic solution.

INTERPOLATION

During the running of the validation problem, numerous large irregular discrepancies were noted when the CSQ II results were compared with the analytic solution. These discrepancies were traced to the technique used to determine tracer particle velocities within a cell. This technique determines tracer particle velocities by interpolating on the velocities associated with the cell containing the tracer particle, independent of the velocities in neighboring cells. This results in errors when the tracer particle is very near one of the boundaries of the cell containing it. Thus, a new interpolation scheme was written to correct this situation. Details of this scheme are presented in appendix A. With this new tracer particle velocity interpolation scheme, the agreement between CSQ II responses and the analytic solution improved from clearly unacceptable to very good.

SYMBOLOGY

A minor change was made to the symbology used by CSQ II in printing out the material plot during the long edit cycle. The ten materials of CSQ II are

designated to be a single material, called *DOT*, and the remaining nine materials are called *X*. Formerly, in the material plot the DOT material was printed out as a single . and the nine X materials were printed out as the digits *2* through *9* and the single letter *A*. This has been changed to print out the nine X materials as the digits *1* through *9*, omitting the letter *A*. It is felt that this is more in keeping with the mental picture one forms of the ten materials, the nine X materials in particular.

AFWL ENGINEERING (AFWLE) EQUATION-OF-STATE

The only real problems encountered in the implementation of CSQ II are related to the inclusion of the AFWLE equation-of-state in CSQ II. Specifically, four problems were encountered in this area.

First, the processing of the AFWLE input variables was greatly complicated by the fact that the many automated features of CSQ II require the special setting of numerous flags and variables at input time. Relatively few of these flags and variables are documented as to purpose, value, or interaction with one another. These had to be discovered by tracing the path of one of the existing CSQ II equations-of-state. Unfortunately, the eight equations-of-state built into CSQ II do not exist as eight distinct modules, but they are mixed together in a rather complex involuted way with numerous additional flags and pointers to point the way through this labyrinth. The result of all this is that there is always a nagging doubt as to whether or not everything has been properly set.

Second, CSQ II employs a temperature-dependent equation-of-state, while that of AFWLE is energy dependent. That is, whenever CSQ II calls the equation-of-state, the calling parameters are density and temperature; AFWLE expects density and internal energy. The basic form of the equation-of-state used in AFWLE is

$$P = f_1(\rho) + \Gamma\rho\varepsilon \qquad (1)$$

where

P = pressure

$f_1(\rho)$ = a given function of the density

Γ = the Grüneisen ratio (a material constant)

ρ = density

ε = internal energy

The problem is to determine ε, given the temperature.

In CSQ II the following relationship between energy and temperature exists:

$$\varepsilon = C_v (t - t_H) + E_H \tag{2}$$

where

C_v = heat capacity of the material

t = temperature

t_H = temperature on the Hugoniot

E_H = mechanical energy due to compression (or expansion) on the Hugoniot

If P_H is the pressure along the Hugoniot, E_H is related to P_H by

$$E_H = \frac{P_H \eta}{2\rho_o} \tag{3}$$

where

$\eta = 1 - \rho_o/\rho$

The AFWLE equation-of-state is of the Mie-Grüneisen form, and can be written

$$\begin{aligned} P &= P_H + \Gamma\rho(\varepsilon - \varepsilon_H) \\ &= P_H - \Gamma\rho E_H + \Gamma\rho\varepsilon \end{aligned} \tag{4}$$

From eq. (4) and eq. (1) we see that

$$f_1(\rho) = P_H - \Gamma\rho E_H$$

or

$$P_H = f_1(\rho) + \Gamma\rho E_H \tag{5}$$

Combining eq. (3) and eq. (5) yields

$$E_H = \frac{f_1(\rho)\eta}{2\rho_o - \rho\Gamma\eta} \tag{6}$$

In general, t_H is given by

$$t_H = t_o e^{\Gamma\eta} + \frac{e^{\Gamma\eta}}{2C_v\rho_o} \int_o^\eta e^{-\Gamma\eta}\, \eta^2 \frac{d}{d\eta}\frac{P_H}{\eta}\, d\eta$$

Unfortunately, the form for P_H yields an expression in the integral which cannot be evaluated simply. The approach employed here was to use an approximation which has the correct limiting values and derivatives near $\rho = \rho_o$.

$$t_H \approx t_o e^{\Gamma\eta} \tag{7}$$

where t_o is the ambient temperature.

The values for E_H and t_H, given by eqs. (6) and (7), respectively, are used in eq. (2) to determine ε for the AFWLE equation-of-state [eq. (1)].

To compute the pressure at low densities ($\rho < \rho_o$) AFWLE uses the form

$$P = \rho\left[H + (\Gamma - H)\sqrt{\mu + 1}\right]\left[\varepsilon - \varepsilon_s\left(1 - \exp N\eta(1 - \eta)\right)\right] \tag{8}$$

where

$\mu = \rho/\rho_o - 1$

ε_s = sublimation energy for the material

$N = C_o^2/\Gamma\varepsilon_s$

C_o = bulk sound speed

$H = \gamma - 1$

γ = ratio of specific heats of the perfect gas

Since neither H nor γ is specifically stated in the AFWLE input, H is set to 0.4, a value which approximates the value for most gases.

In this case ($\rho < \rho_o$), ε is computed from

$$\varepsilon = C_v(t - t_H)$$

When $\rho = \rho_o$, eq. (8) reduces to

$$P = \Gamma\rho\varepsilon = \Gamma\rho C_v(t - t_o)$$

and is continuous with eq. (1) at this density.

Third, when CSQ II determines the pressure within a mixed material cell, it first determines the pressure for each material in the cell and does a volume averaging to obtain the net pressure for the entire cell. Having the cell pressure, CSQ II then adjusts the density of each material in the cell so as to yield the

computed cell pressure for each individual material. This process of individual material density adjustment is essentially a process of Newtonian iteration and requires that the derivative of pressure with respect to density be known for each material in the cell. This derivative must also be continuous and well behaved in the region where this calculation is to take place.

Unfortunately, the form for pressure in AFWLE does not have derivatives which are well behaved. In particular, the function $f_1(\rho)$ of eq. (1) is a piecewise linear function and thus the derivative of pressure with respect to density is a step function. Similarly, the derivative of pressure given by eq. (7) behaves very erratically over much of the range $\rho < \rho_o$. The result of this has been convergence failure when computing densities in mixed cells. Such convergence failure causes automatic run termination of CSQ II. Much effort has been spent attempting to correct this problem but without success. Indeed, there may not be a solution strictly within the framework of the AFWLE equation-of-state.

Fourth, the AFWLE equation-of-state is history dependent. That is, the exact form of the equation-of-state depends on the previous states of the material under consideration. The equation-of-state behaves very much like a porous material, or foam. On loading the material compresses elasticly up to a critical pressure, from which point it compresses plasticly. On release it does not unload along the load path but rather unloads along an elastic path from the point of maximum compression. On reloading the material compresses elasticly up to the previous point of maximum compression where it again continues its plastic compression. This requires that the state of maximum compression be retained among the cell storage variables for each material. Because this would require considerable additional storage and a complete rearrangement of the CSQ II storage scheme, it was decided that this feature would not be included at this time. The scheme implemented in CSQ II is to allow the material to unload along the original load path. On recompression the material loads along the same path as the original compression.

The modified input required for the AFWLE equation-of-state is presented in appendix B.

SECTION 4
EVALUATION

Originally it had been intended to evaluate CSQ II by comparing the results of the Pre-Dice Throw Experiment with the results of a CSQ II simulation of that experiment. Briefly stated, the Pre-Dice Throw Experiment consisted of the detonation of a 100-ton charge of TNT over a multilayered earth medium and the examination of the velocities and displacements produced in the underlying medium at various test points out to a 50-msec problem time. However, because of difficulties in the treatment of mixed material cells (section 3), no run was completed beyond 1.9 msec; this is just a little beyond the time of complete detonation of the TNT and no significant motion was imparted to the underlying earth by this time. Thus, no significant evaluation of CSQ II was possible from these runs.

A partial evaluation of CSQ II without the AFWLE equation-of-state was made by comparing the exact analytic solution of a special test case with the CSQ II solution for that problem. The test case consisted of a constant 2000-psi pressure applied uniformly over the interior surface of a spherical cavity in a layered geology (fig. 1). Of particular interest were the shock arrival times and the velocities and displacements produced by the shock waves at various target points near the interface between the two materials. In general, shocks near the interface are a result of direct waves and waves reflected or refracted at the interface. The results of the CSQ II run, together with the analytic solutions, for selected peri-interfacial target points are given in figures 2 through 7.

The only problem encountered during the running of the test case was the large discrepancies in velocities and displacements caused by the CSQ II interpolation schemes. This problem is thoroughly discussed in section 3; the new corrective interpolation technique is presented in appendix A.

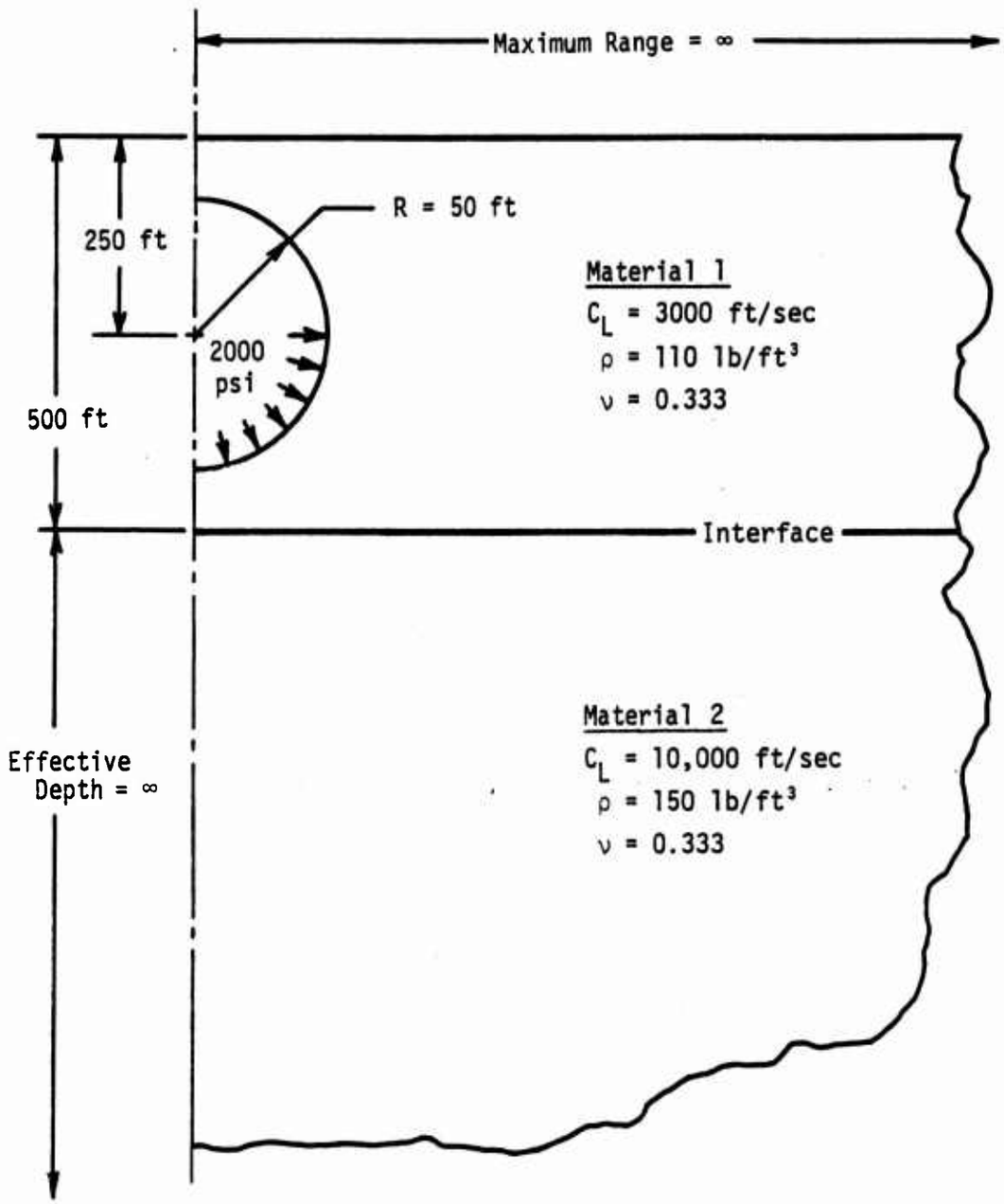

Figure 1. Geometry of CSQ II Test Problem

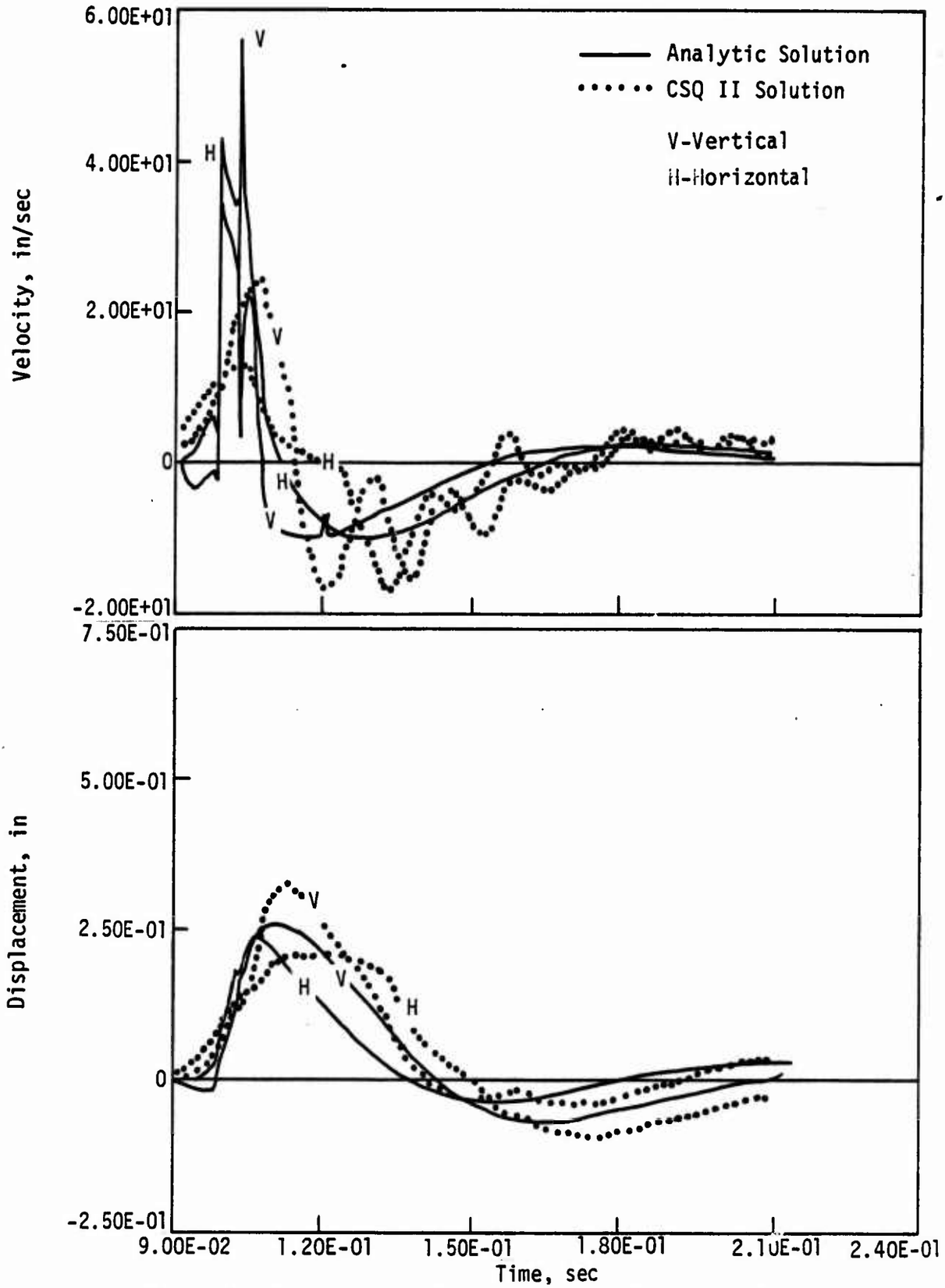

Figure 2. Responses at 250-Foot Range, 490-Foot Depth

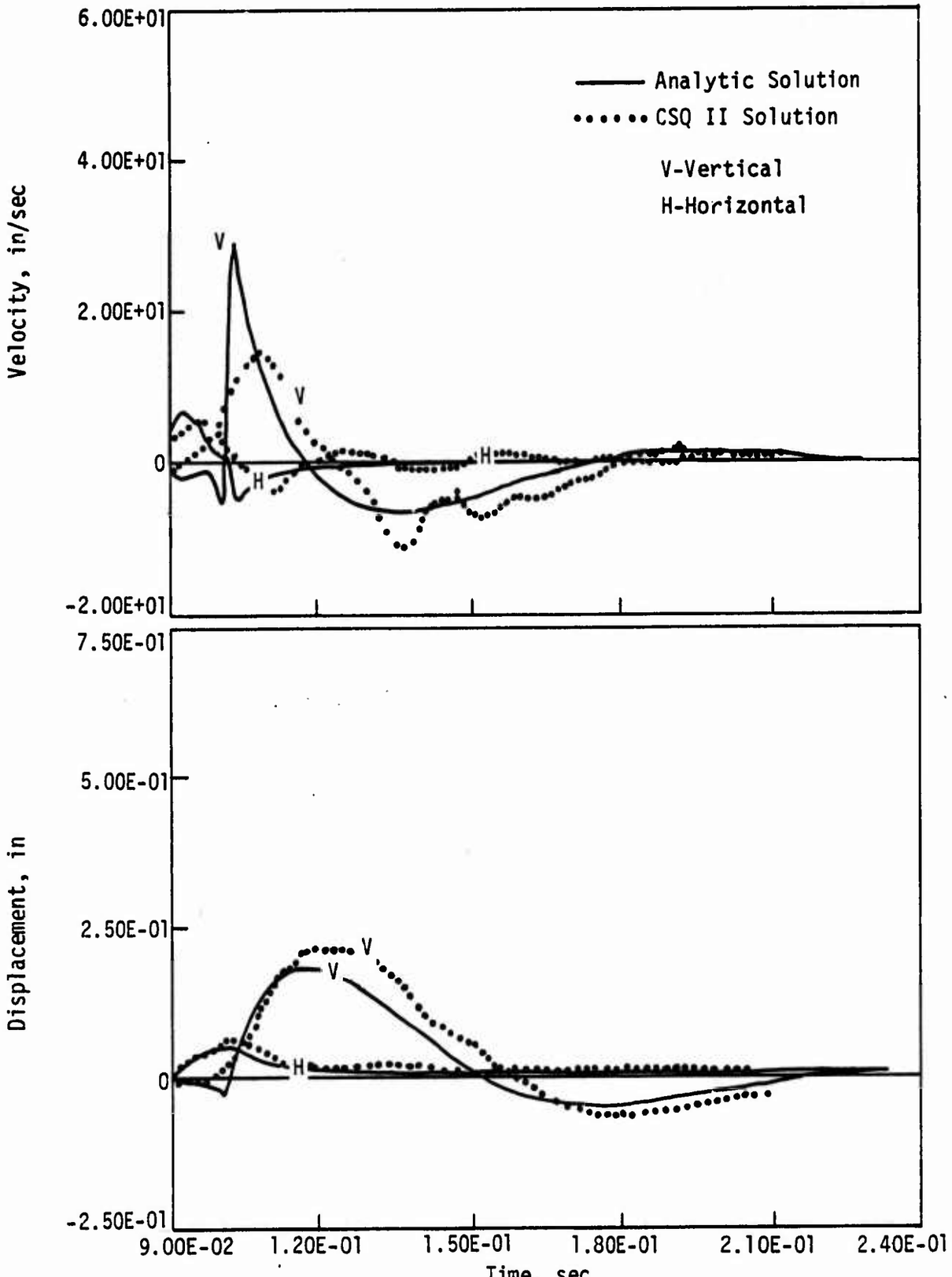

Figure 3. Responses at 250-Foot Range, 510-Foot Depth

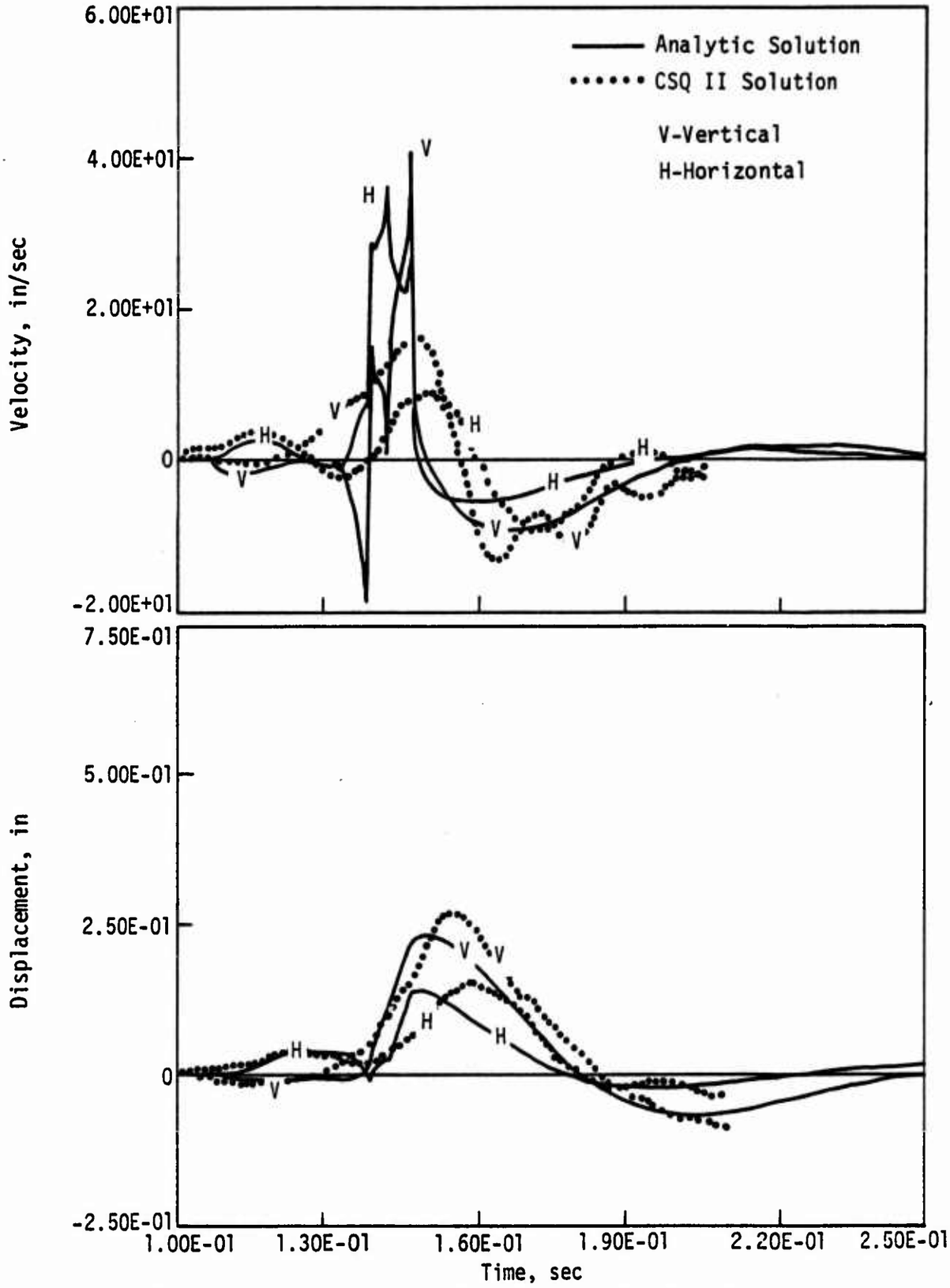

Figure 4. Responses at 400-Foot Range, 490-Foot Depth

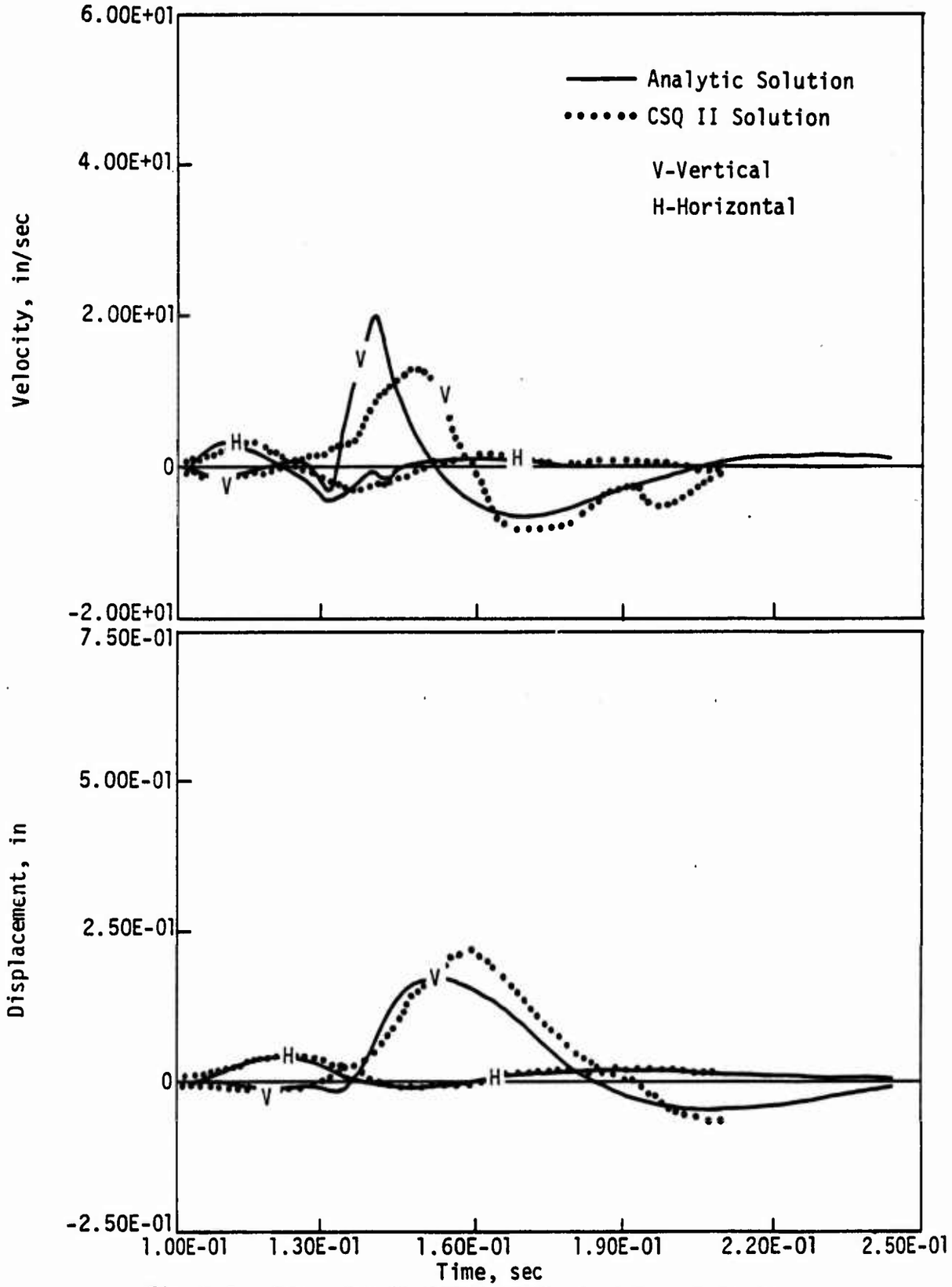

Figure 5. Responses at 400-Foot Range, 510-Foot Depth

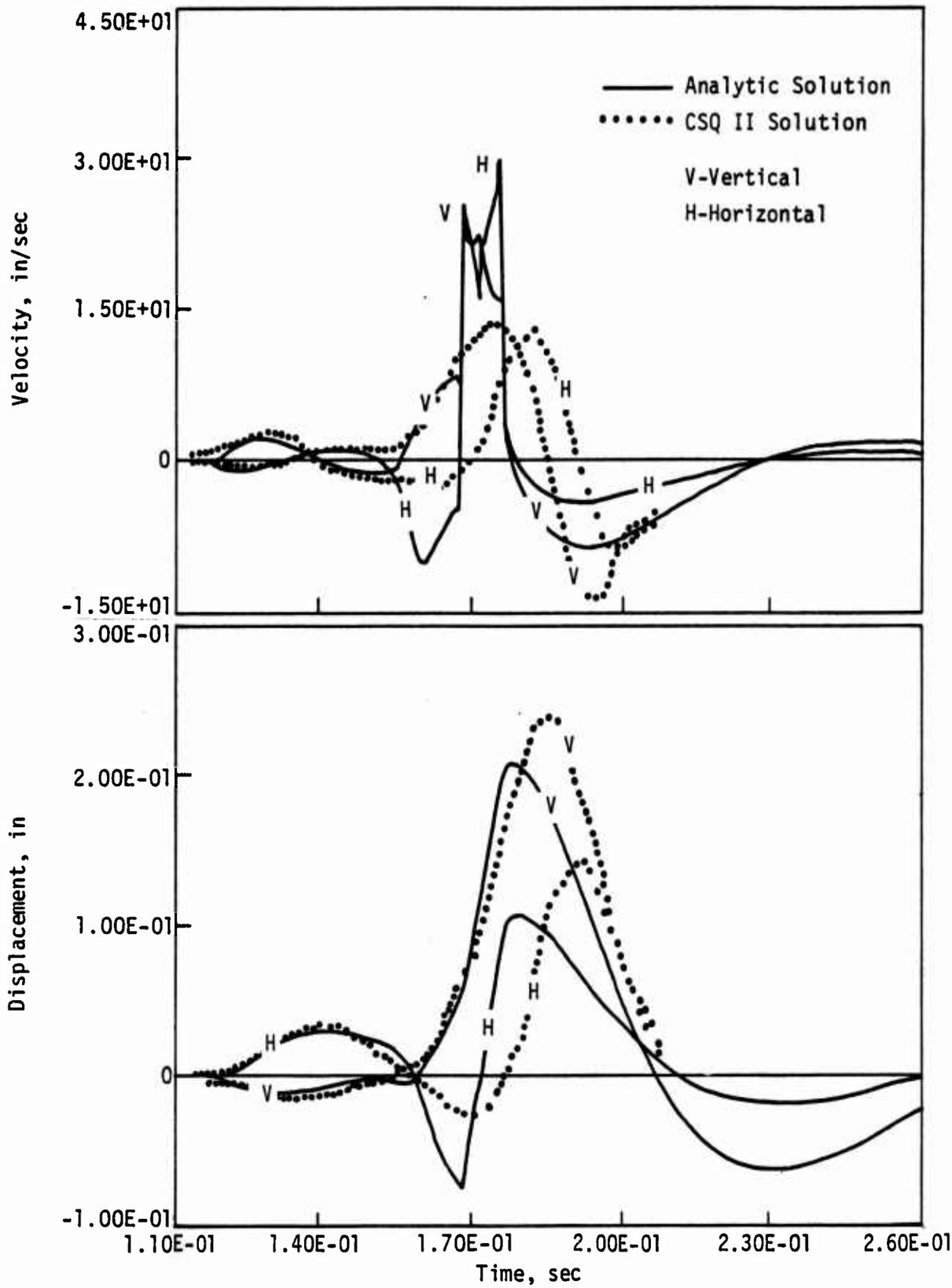

Figure 6. Responses at 500-Foot Range, 490-Foot Depth

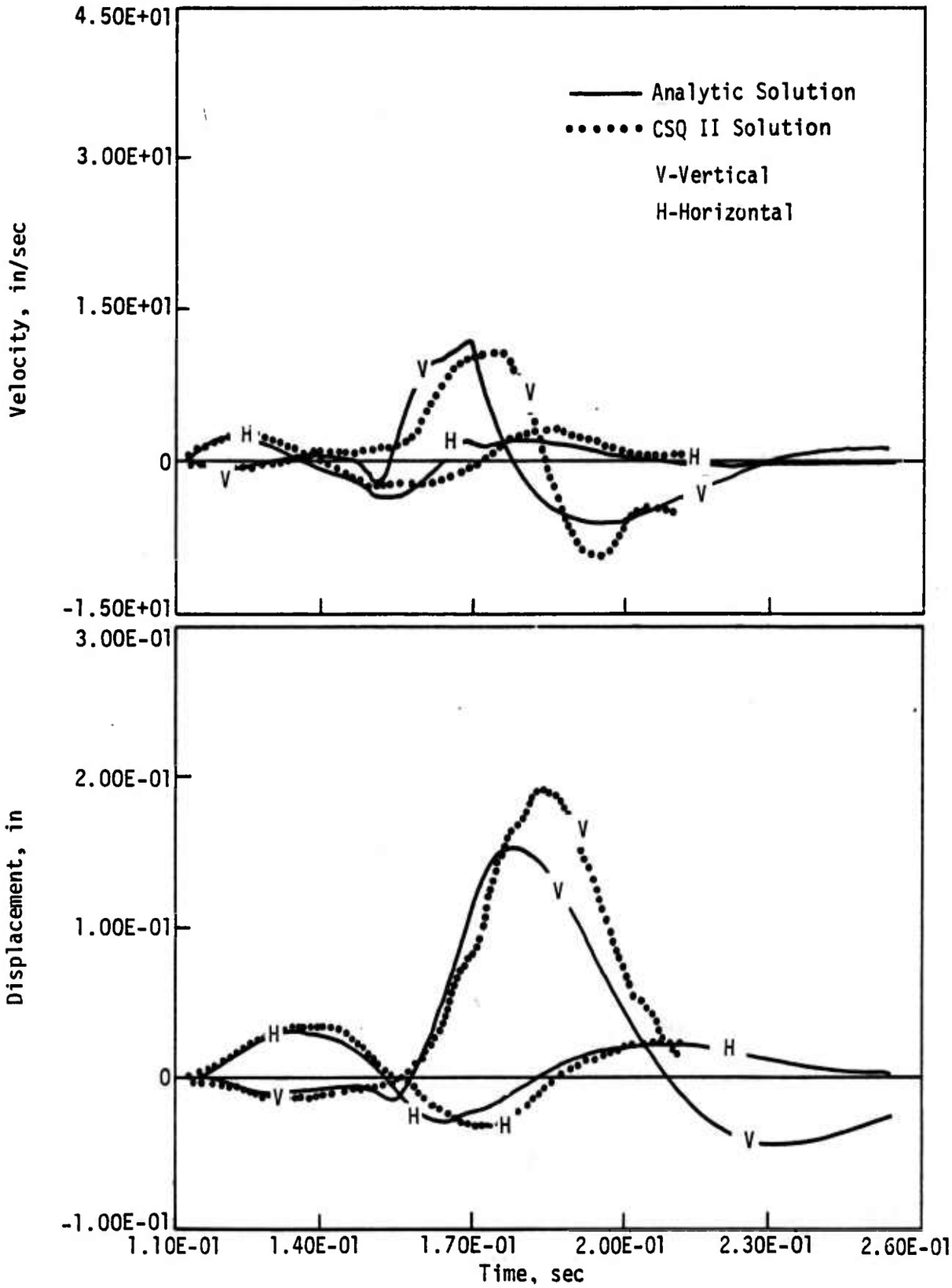

Figure 7. Responses at 500-Foot Range, 510-Foot Depth

SECTION 5
CONCLUSIONS AND RECOMMENDATIONS

There are two avenues of approach open for the future use of CSQ II. First, CSQ II could be used in its present form, i.e., without the AFWLE equation-of-state. However, when problems to be run with CSQ II are defined in terms of the AFWLE equation-of-state, as will often be the case, it will be necessary to convert the AFWLE input parameters to a form compatible with that built into the CSQ II equation-of-state. This means approximating the jointed linear AFWLE equation-of-state with a polynomial. A computer program could be devised to accomplish this. The second approach is to spend the additional time and money required to fully implement the AFWLE equation-of-state into CSQ II. Because of the highly involuted logic flow of CSQ II and the complex iteration of its many automated features, this would be no simple task. Communications with Dr. S. L. Thompson of Sandia Laboratories, the author of CSQ II, have confirmed this assessment. However, should this approach be chosen, it would be advisable to contact Dr. Thompson since he has as much knowledge as anyone in the internal complexities of CSQ II.

APPENDIX A

IMPROVED TECHNIQUE FOR COMPUTING INTERPOLATED VELOCITIES OF TRACER PARTICLES

Formerly when a tracer particle, T (fig. A1), was located in cell (i,j), the x-component of its velocity, $V_x(T)$, was calculated from

$$V_x(T) = \lambda\left[V_x(i+1,j) + (1-\lambda)\right]\left[V_x(i,j)\right]$$

where

$$\lambda = \frac{X(T) - X(i)}{X(i+1) - X(i)}$$

$V_x(i+1,j)$ = velocity (x-component) of the right boundary of cell (i,j)

$V_x(i,j)$ = velocity of the left boundary of cell (i,j)

$X(T)$ = x-coordinate of tracer particle

$X(i)$ = x-coordinate of left boundary

$X(i+1)$ = x-coordinate of right boundary

The y-component of the tracer particle velocity, $V_y(T)$, was calculated in a similar manner.

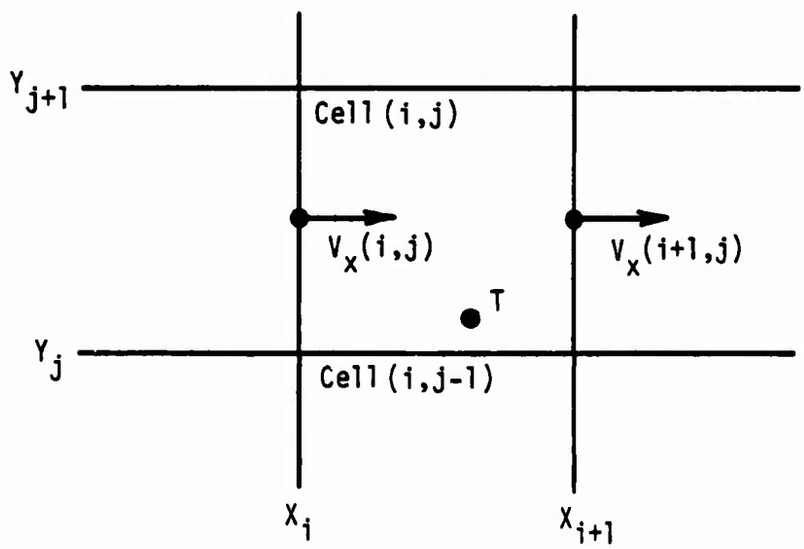

Figure A1. Tracer Particle Velocity Interpolation in CSQ II

This technique led to errors in the calculated velocities when the tracer particle was near one of the cell boundaries. For example, when the particle is on or very near the lower boundary of cell (i,j), it is expected that the calculated particle velocity would be influenced as much by the velocities of the cell below, cell (i,j - 1), as by the velocities of cell (i,j) itself. In the former technique, however, the particle velocity was not affected by cell (i,j - 1) at all; this led to very irregular velocity behavior when the position of the particle fluctuated from one side of the boundary to the other.

In the improved interpolation scheme, when a tracer particle is located in cell (i,j) its velocity is calculated from the velocities associated with cell (i,j) and the velocities of one or more of the neighboring cells. The example presented in figure A2 illustrates this new technique.

Since T is located in the lower half of cell (i,j), the x-component of the velocity of T, $V_x(T)$, will be interpolated from the velocities of the cell below cell (i,j); i.e., cell (i,j - 1). If T is in the upper half of cell (i,j), interpolation would be carried out with cell (i,j + 1), the cell above cell (i,j). The interpolation is bilinear; i.e., linear in both the x- and y-directions.

First velocities are interpolated in the x-direction in a manner identical to that in the former interpolation scheme. This yields for cell (i,j) and cell (i,j - 1), respectively,

$$V_x(T,j) = \lambda\, V_x(i + 1,j) + (1 - \lambda)\, V_x(i,j)$$

$$V_x(T,j - 1) = \lambda\, V_x(i + 1,j - 1) + (1 - \lambda)\, V_x(i,j - 1)$$

where

$$\lambda = \frac{X(T) - X(i)}{X(i + 1) - X(i)}$$

$V_x(i,j)$ = velocity of left boundary of cell (i,j)

$V_x(i + 1,j)$ = velocity of right boundary of cell (i,j)

$V_x(i,j - 1)$ = velocity of left boundary of cell (i,j - 1)

$V_x(i + 1,j - 1)$ = velocity of right boundary of cell (i,j - 1)

Next, the values $V_x(T,j)$ and $V_x(T,j - 1)$ are interpolated (linearly) in the y-direction to obtain $V_x(T)$.

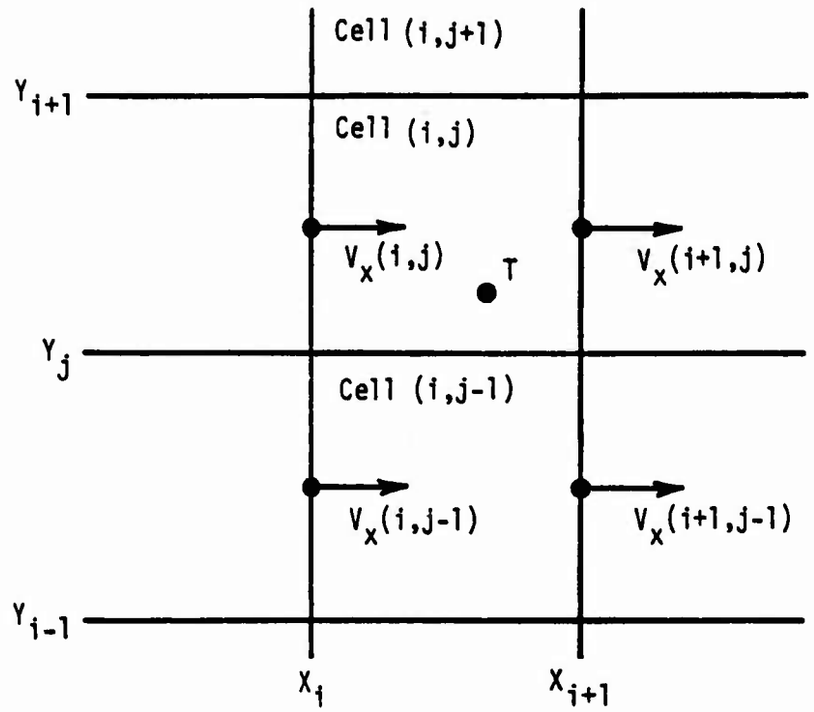

Figure A2. Improved Tracer Particle Velocity Interpolation for CSQ II

If $\overline{Y}_j$ denotes the y-coordinate of the center of cell (i,j) and $\overline{Y}_{j-1}$ denotes the y-coordinate of the center of cell (i,j - 1),

$$\overline{Y}_j = \left(Y_j + Y_{j+1}\right)/2$$

and

$$\overline{Y}_{j-1} = \left(Y_{j-1} + Y_j\right)/2$$

See figure A2. If

$$\lambda_y = \frac{y(T) - \overline{Y}_j}{\overline{Y}_{j-1} - \overline{Y}_j}$$

where y(T) is the y-coordinate of the tracer particle,

$$V_x(T) = \lambda_y\left[V_x(T,j) + (1 - \lambda)\, V_x(T,j-1)\right]$$

It should be noted that this bilinear interpolation is commutative. That is, the results would be exactly the same had the first interpolation been in the y-direction followed by interpolation in the x-direction. A similar bilinear interpolation process is used to determine $V_y(T)$, the y-component of the tracer particle velocity.

APPENDIX B
MODIFIED INPUT INSTRUCTIONS

Complete input instructions for CSQ II are given in references 2 and 3. The following modifications do not change the basic CSQ II input but rather supplement that input for the AFWLE equation-of-state.

CARD SET 3: ANALYTIC EQUATION-OF-STATE DATA

Card set 3 (ref. 3) provides the equation-of-state data for the various materials in the problem to be run with CSQGEN. When the AFWLE equation-of-state is to be used, the following cards must be included, one set for each AFWLE type material. There is no problem in mixing AFWLE type materials with regular CSQ II equation-of-state materials in a given problem. Equation-of-state parameters for CSQ II type materials are given in reference 2. This card set is in the CSQGEN input stream.

Card 3.1 - FORMAT (I3, I5, I2, 5A10, 2E10.3)

Variable	Columns	Description
1	1-3	Equation-of-State Number. Always -1 to -20.
2	4-8	Must be zero for AFWLE equation-of-state read in from cards; nonzero for library equations-of-state.
3	9-10	Used only by library equation-of-state routines; set to blank.
4-8	11-60	Identification Label. Any BCD information.

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2. Thompson, S. L., *Improvements in the CHART D Energy Flow-Hydrodynamic Code V: 1972/1973 Modifications*, SLA-73-0477, Sandia Laboratories, Albuquerque, New Mexico, October 1973.
3. Thompson, S. L., *Input Instructions for CSQ II - A Ten Material Version of CSQ*, RS 5166/135, Internal Memorandum, Sandia Laboratories, Albuquerque, New Mexico, October 1975.

Variable	Columns	Description
9	61-70	RHUG - Initial Density for Hugoniot Calculation. If zero, calculation is skipped; if negative, the initial density, ρ_o (Card 3.2), is taken to be the reference density.
10	71-80	THUG - Initial Temperature for Hugoniot Calculation. If zero, calculation is skipped; if negative, the initial temperature, T_o (Card 3.2), is taken to be the reference temperature.

Card 3.2 - FORMAT (8E10.3)

Variable	Columns	Description
1	1-10	Number of Elements in Material
2	11-20	Switch for Type of Equation-of-State. Must be -4 for AFWLE equation-of-state.
3	21-30	ρ_o - Reference Density
4	31-40	T_o - Reference Temperature. If $T_o \leq 0$, code sets T_o = 0.02567785 eV (298°K).
5	41-50	Blank
6	51-60	Blank
7	61-70	Γ_o - Reference Grüneisen Coefficient
8	71-80	Blank

Card 3.3 - FORMAT (8E10.3)

Variable	Columns	Description
9	1-10	ρ_{min} - Lowest Allowed Solid Density. If $\rho_{min} \leq 0$, code sets $\rho_{min} = 0.8\ \rho_o$.
10	11-20	Blank
11	21-30	C_v - Heat Capacity. If $C_v \leq 0$, code sets C_v = 3NoK.
12	31-40	ε_s - Sublimation Energy (cgs units)
13	41-50	V_L - Loading Poisson's Ratio
14	51-60	V_u - Unloading Poisson's Ratio
15	61-70	CL_1 -] Constants Used to Describe Density/Pressure
16	71-80	CL_2 -] Relationship in AFWLE

Card 3.4 - FORMAT (8E10.3)

Variable	Columns	Description	
17	1-10	CU	Constants Used to Describe Density/ Pressure Relationship in AFWLE
18	11-20	CZ	
19	21-30	P_1	
20	31-40	AM2	
21	41-50	AM3	
22	51-60	BKM	
23	61-70	AMS = MUSTAR	
24	71-80	Blank	

Card 3.5 - FORMAT (5(F5.0,E10.3))

There is one pair of the following variables for each element in variable 1 of card 3.2.

I = 1, number of elements

Odd Variable — Z(I) - Atomic Number of Element

Even Variable — Unnormalized Atomic Number Fraction of Element or Unnormalized Atomic Weight Fraction of Element. All elements should be defined in the same way.

CARD SET 12: YIELD CRITERIA

When the elastic/plastic option is to be used, the following card must be included in the CSQ II input card stream. There must be one card for each AFWLE type material. When the material is to be treated hydrodynamically, a blank card must be entered.

Card 12.1 - FORMAT (8E10.3)

Variable	Columns	Description	
1	1-10	VM2 (dynes/cm^2)	Constants Used to Describe AFWLE Yield Curve
2-4	11-40	Blank	
5	41-50	ST2	
6	51-60	Y2	
7	61-70	S2	

Variable	Columns	Description
8	71-80	AFWLE Flag. Must be ≠ 0 to treat variables as AFWLE variables; if flag = 0, variables will receive a CSQ II interpretation.

ABBREVIATIONS, ACRONYMS, AND SYMBOLS

C_L	elastic wave speed
C_o	bulk sound speed
C_v	heat capacity of material
E_H	mechanical energy due to compression (or expansion) on Hugoniot
H	$\gamma - 1$
K	Boltzmann's constant
N	$C_o^2/\Gamma\varepsilon_s$
No	number of atoms per unit mass
P	pressure
P_H	pressure along Hugoniot
T	tracer particle
$f_1(\rho)$	function relating pressure to density
t	temperature
t_H	temperature on Hugoniot
t_o	ambient temperature
Γ	Grüneisen ratio (material constant)
γ	ratio of specific heats of the perfect gas
ε	internal energy
ε_s	sublimation energy for material
η	$1 - \rho_o/\rho$
μ	$\rho/\rho_o - 1$
ν	Poisson's ratio
ρ	density

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    SUL
    DE
    DEP
    DES
    DY
    DYM
AU/AUL/LDE/ED Dir Civ Engr
USAF/RDQSM/RDQ 5
RADC/Doc Lib
SAMSO/MNNH/Norton AFB
USAFA/DFSLB/FJSRL/DFCE
Dir, USA Engr WW Exp Sta, Vicksburg
    WESRL
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    AMCPM-NXE-FB
USA Ohio River Div Lab Corps Engr
    ORDLBVR
USA, Ch Engr/ENGMC-EM
NCEL/Mr Algood/Port Heuneme CA
Dept of Navy
    Ofc Ch Navy Ops
    Ofc Navy Rsch
NOL/NRL Code 730 & 2027
NWO/Code 753, China Lake CA
Dept of Interior, Bureau of Mines,
Fed Cen/Dr Obert/Denver CO
Bureau of Mines, Twin Cities Rsch Cen/
Dr Atchison, Minneapolis MN
Sandia Lab, Livermore CA
Sandia Lab, Albuquerque NM
    Info Dist Div
    Dr Merritt
    Mr Broyles
    Mr Herrman
    Mr Weart
    Mr Chabi
Aerospace Corp/Dr Mather
Agbabian Asso/Dr Agbabian/Los Angeles
Analytic Svcs, Inc/Mr Hesselbacher/
Falls Church VA
Applied Theory Inc/Dr Trulio/Los Angeles
The Boeing Co, Seattle
    Mr Carlson
    Mr Pyrdahl
Calif Instit of Tech, Pasadena
    Dr Ahrens
    Dr Silver
Calif Rsch & Tech, Inc./M Rosenblat/
Woodland Hills
Civil Nuclear Sys, Inc./Dr Crawford/
Albuquerque NM
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Falls Church VA
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Teledyne, Brown Engr/SETAC, Mr Patel/
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Terra Tek Inc./Dr Pratt/Salt Lake City
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U of Texas/W. Muehlberger/Austin
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Weidlinger Asso/Dr Isenberg/Menlo Park
J.H. Wiggins Co/Dr Collins/Redondo Beach
ERDA/Doc Cont
DDC/TCA
DDR&E/Asst Dir Strat Wpns
DIA, Wash DC
LtCol Cavanaugh
DIAAP-8B
DIAST-3
Diamond Lab/Lib
DNA, Wash DC
STTL
SPSS
STSI
DDST
FCDNA/FCSD-A4/Kirtland AFB NM
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